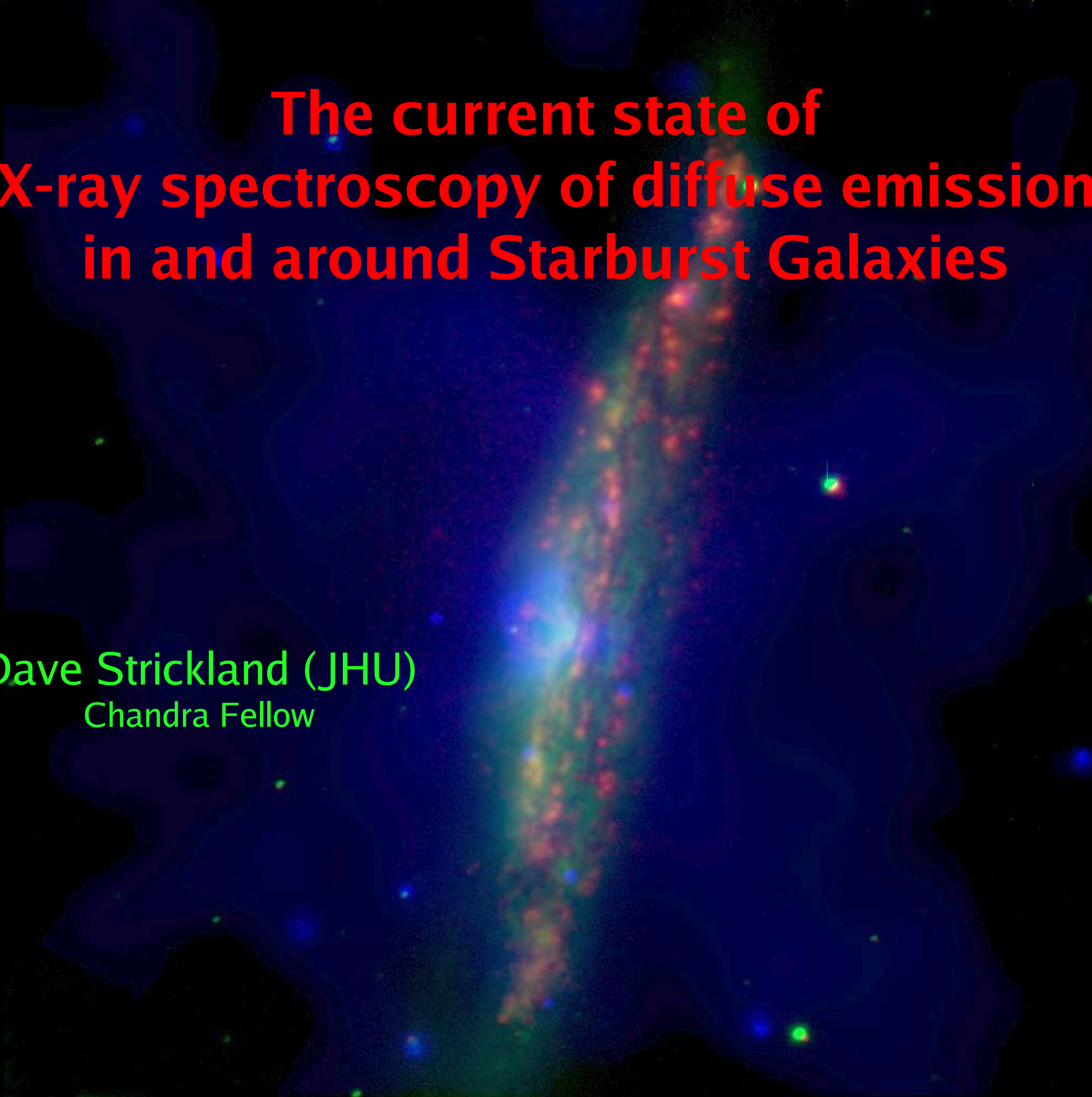
The current state of X-ray spectroscopy of diffuse emission in and around Starburst Galaxies

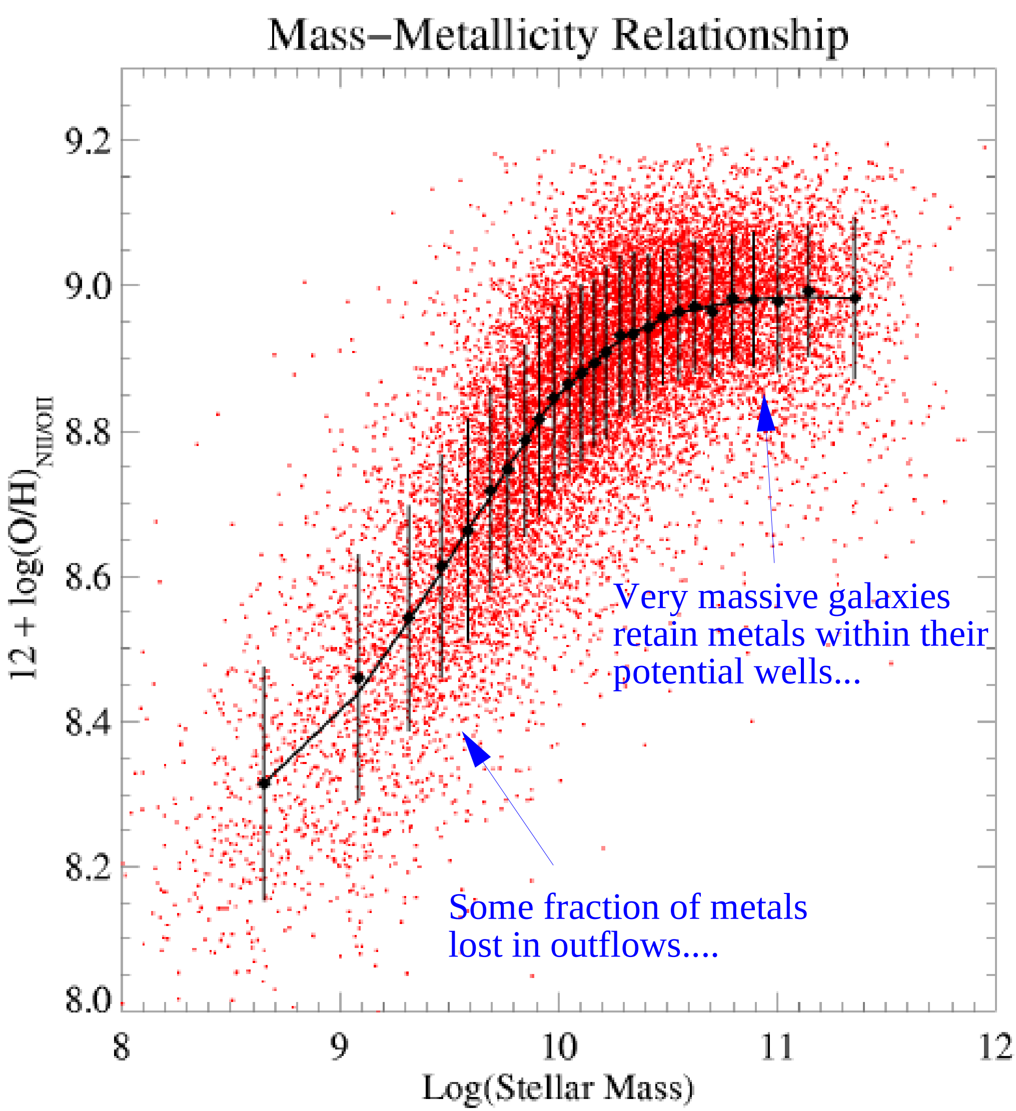


Dave Strickland (JHU)
Chandra Fellow

Outline

- Motivation: Metal loss from galaxies and SN-driven galactic outflows
- Measuring the abundance in the soft thermal plasmas...
  - Lessons from low resolution spectroscopy.
    - Spatial complexity, and then more spectral complexity.
    - No absolute abundance determinations.
  - Toward higher spectral resolution.
- Mapping the kinematics of the hot gas (in the future).
- Summary, and implications for Constellation-X.

Indirect evidence for metal ejection



Tremonti, 2003, PhD thesis

- A galaxy mass-metallicity relationship has been hinted at for a long time, but the SDSS provides orders of magnitudes more data (~100 000 galaxies).
- Theoretical models of galactic chemical evolution with metal-loss due to winds predict this form of M-Z relationship (including flattening), e.g. Larson 1974
- Alternative explanation - low mass galaxies less evolved, less processing, BUT not all galaxies gas rich.

Methods of getting metals out of galaxies

Name	Observational evidence?	Redshift of operation	Current issues	Notes	Example Reference
Pop III stars	**none yet**	**z > 5**	**Unconstrained**	**Cooling time.**	Schneider et al 2002; Pettini et al 2001
Ram pressure stripping	**Exists? Yes**	**z < 1 only.**	**Densest regions Efficacy unknown.**	**...**	Murakami & Babul 1999; White 1991
Galaxy collisions	**Exist? Yes Loss to IGM?**	**Galaxy form. on...**	**Rarity? Efficacy... unknown.**	Gnedin 1998	
SN II-driven winds (star-forming galaxies)	**Exist? Yes Loss to IGM? Unknown?**	**Galaxy formation onwards**	**Quantitative efficacy unknown**	**Metal-enriched! +Energy.**	Heckman et al 1990; Tegmark et al 1993
SN Ia-driven winds from ellipticals	**No direct obs. evidence!**	**~1 Gyr after elliptical formation?**	**Possibly do not exist.**	**monolithic collapse**	Larson 1974; Pipino et al 2002
Something else?...		**...**	**...**	**...**	**...**

6) Gas escapes galaxy halo and reaches the IGM?

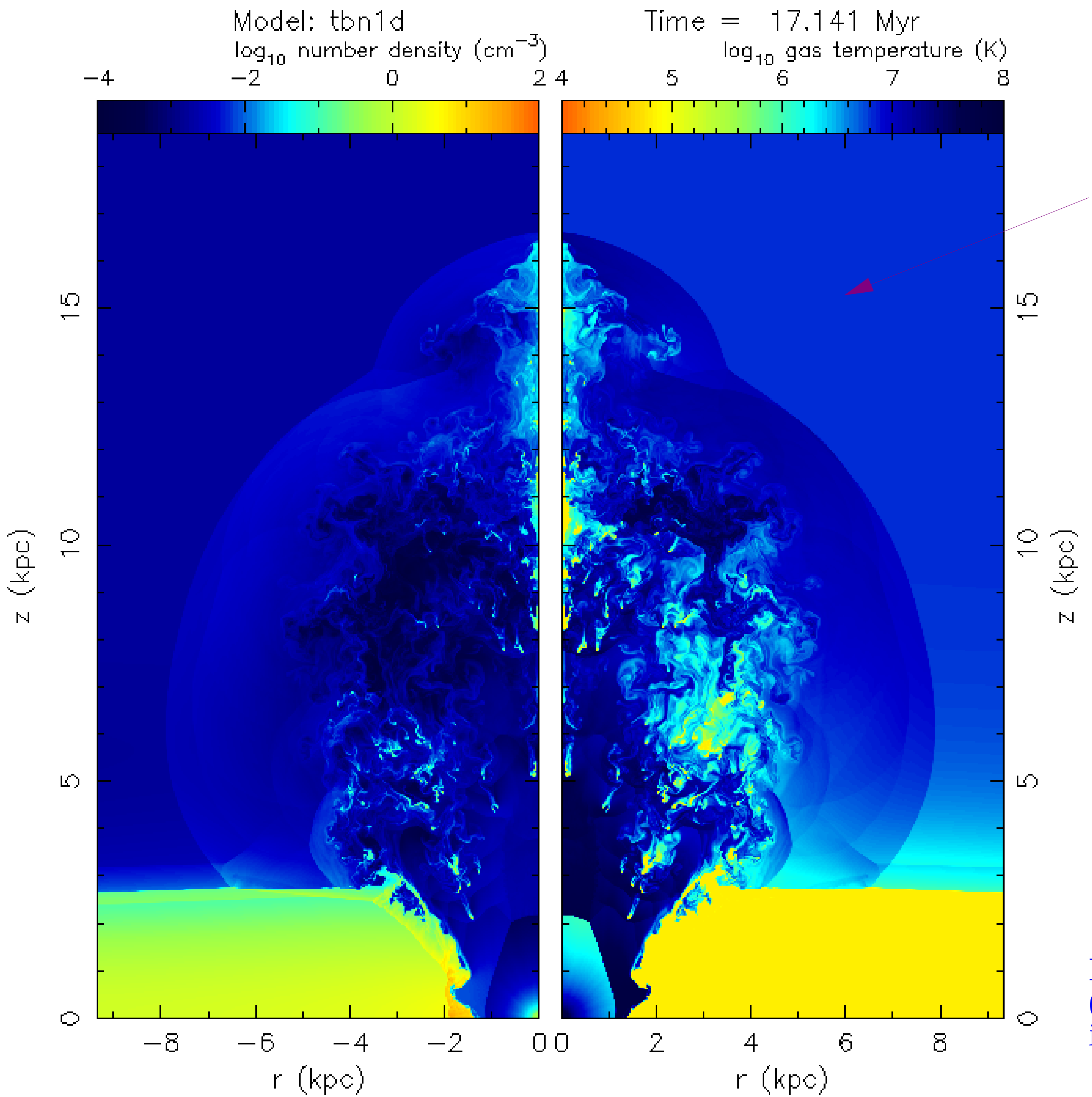
5) Entrains and accelerates cool dense ambient gas

4) Expands into halo (v~1000's km/s)

3) Breaks out along poles of galaxy

2) High P, T gas of merged SNe expands

1) Multiple supernovae for ~40 Myr after SF episode, ~10^6 SNe.

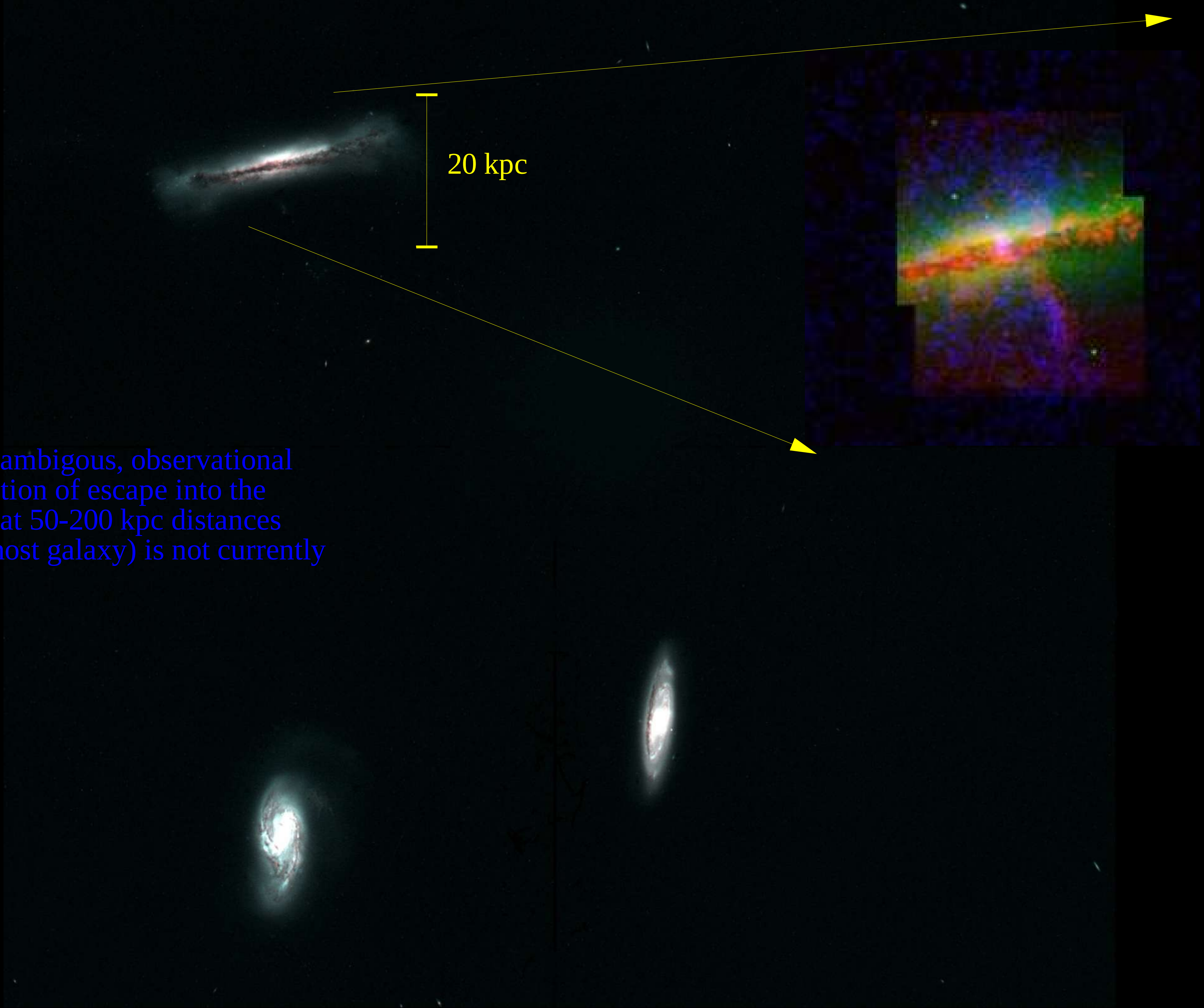


Halo region (gas is tenuous, possibly hot)

Disk of galaxy (denser, cooler, interstellar gas)

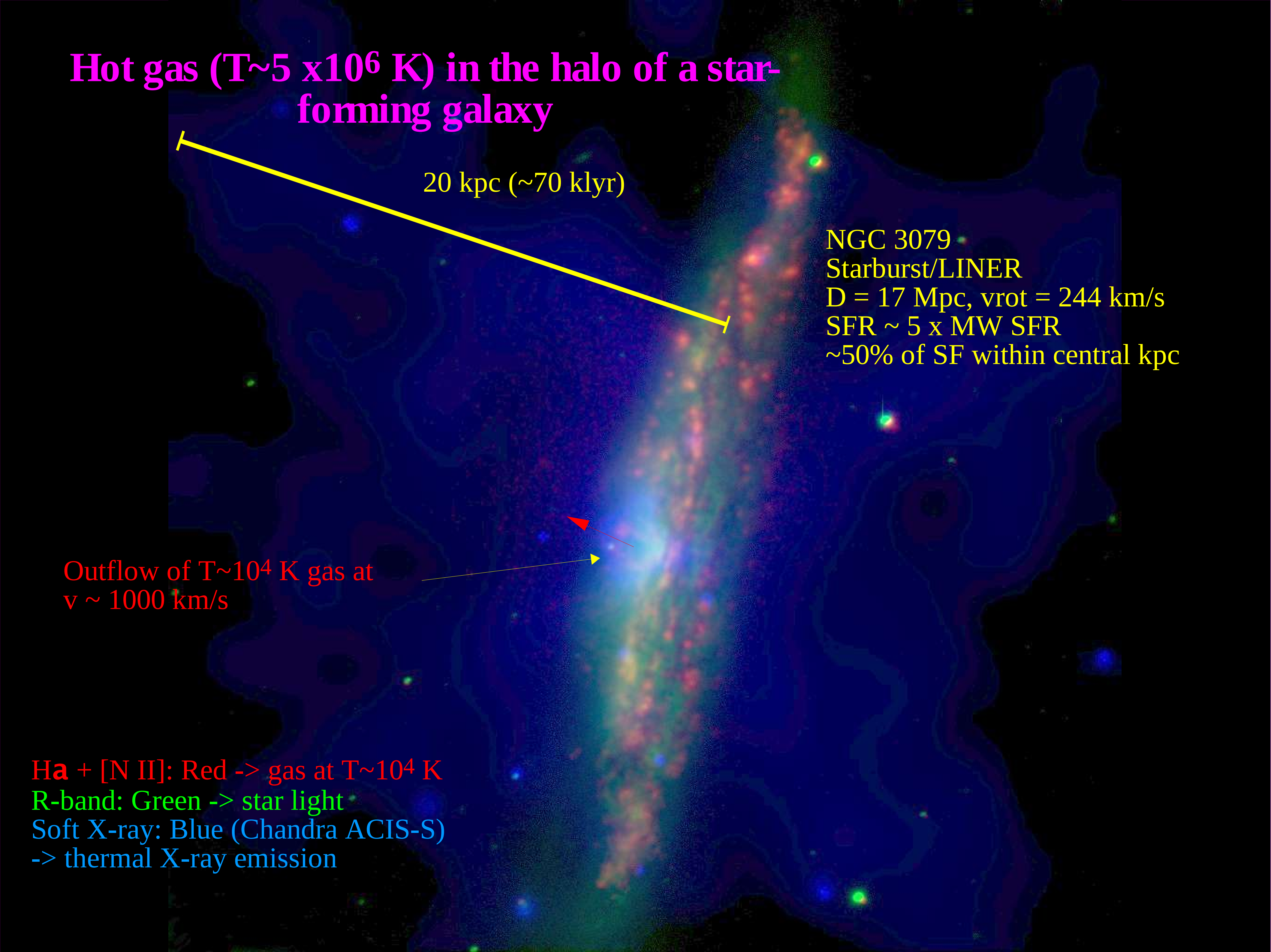
Central star-forming region

Do the metals escape into the IGM?

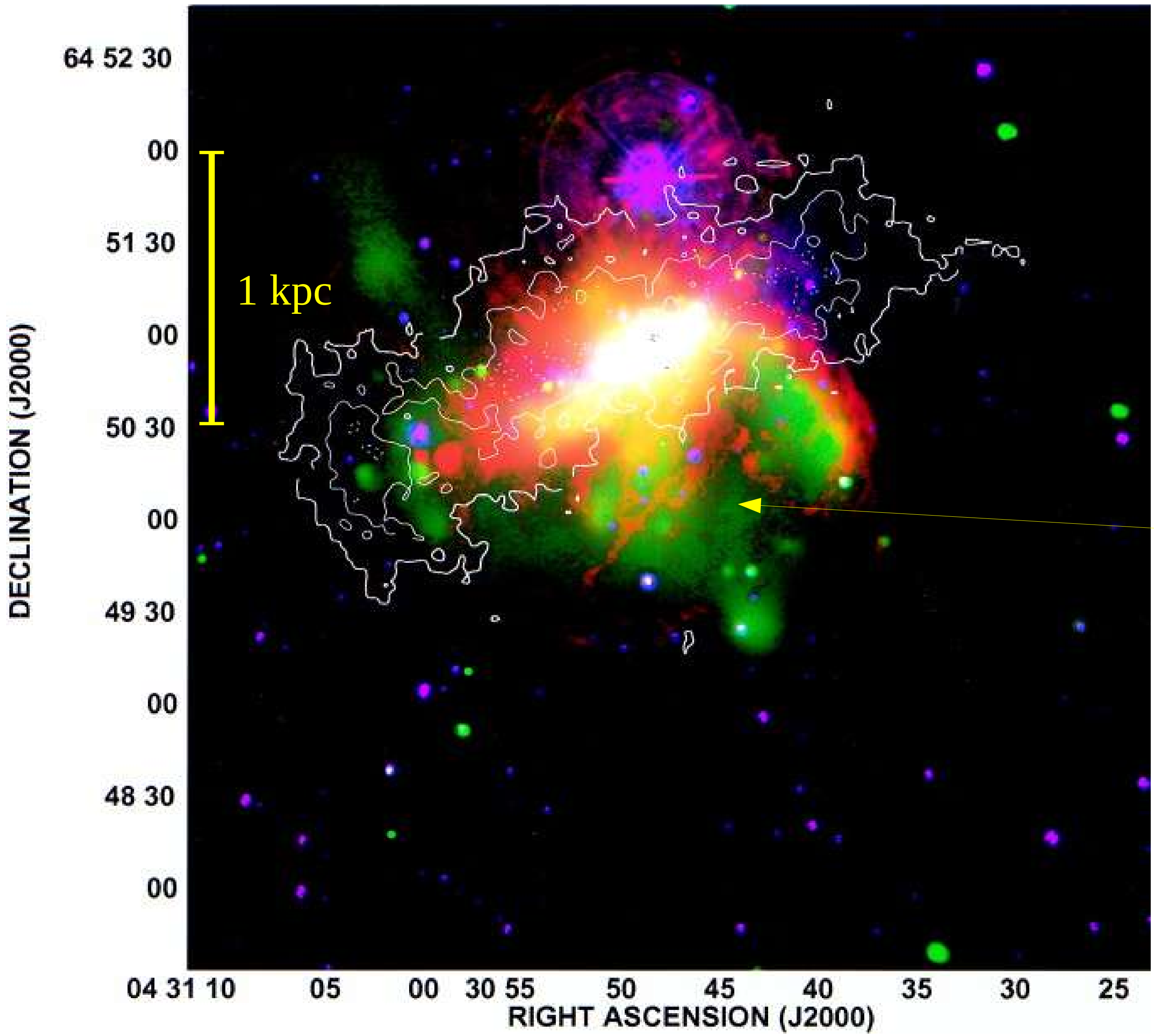


Direct, unambigous, observational determination of escape into the IGM (i.e. at 50-200 kpc distances from the host galaxy) is not currently feasible...

Hot gas ($T \sim 5 \times 10^6$ K) in the halo of a star-forming galaxy



Loss of metals from dwarf galaxies?



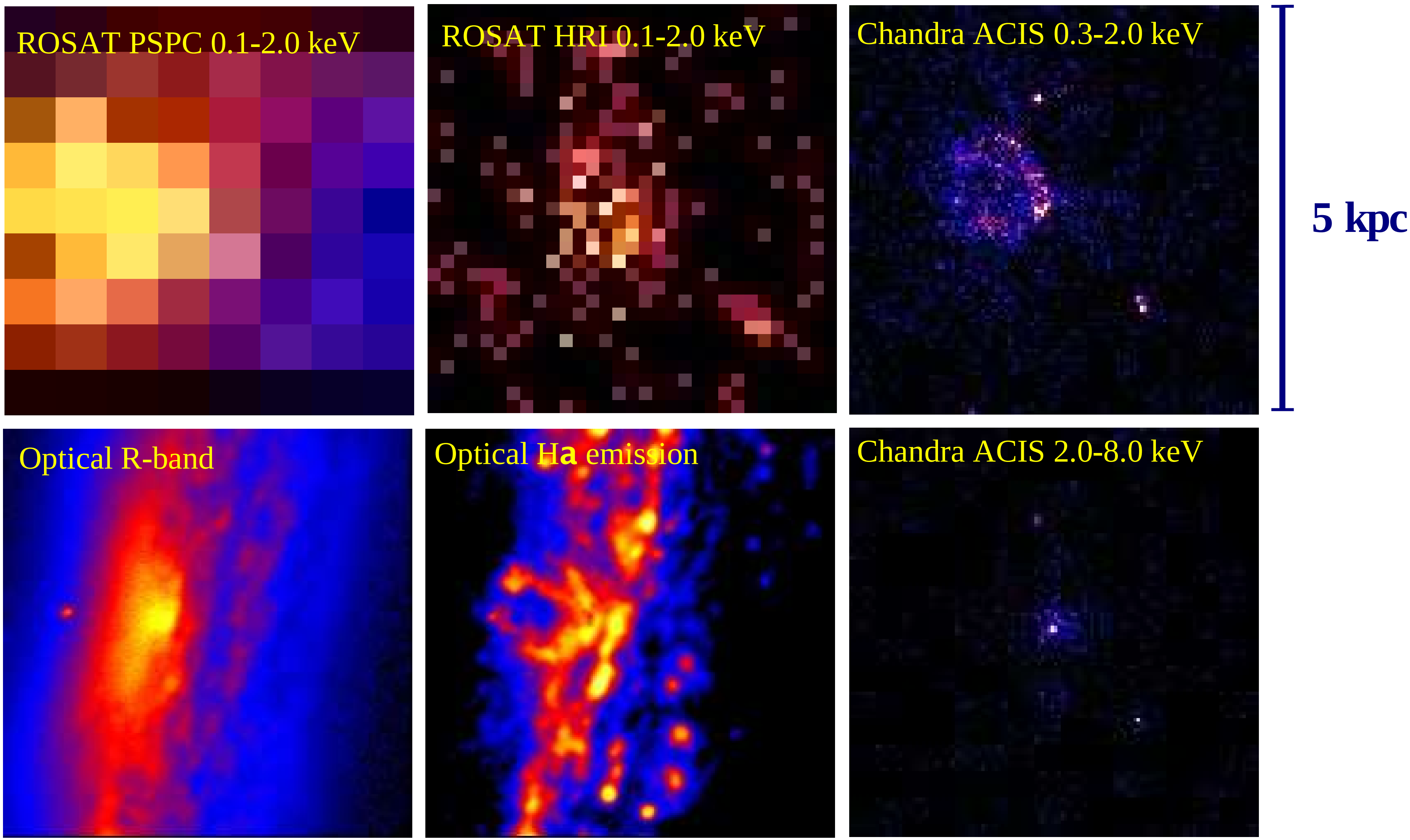
Martin et al 2002
Red: Hα
Green: X-ray
Blue: R-band
Contours: HI

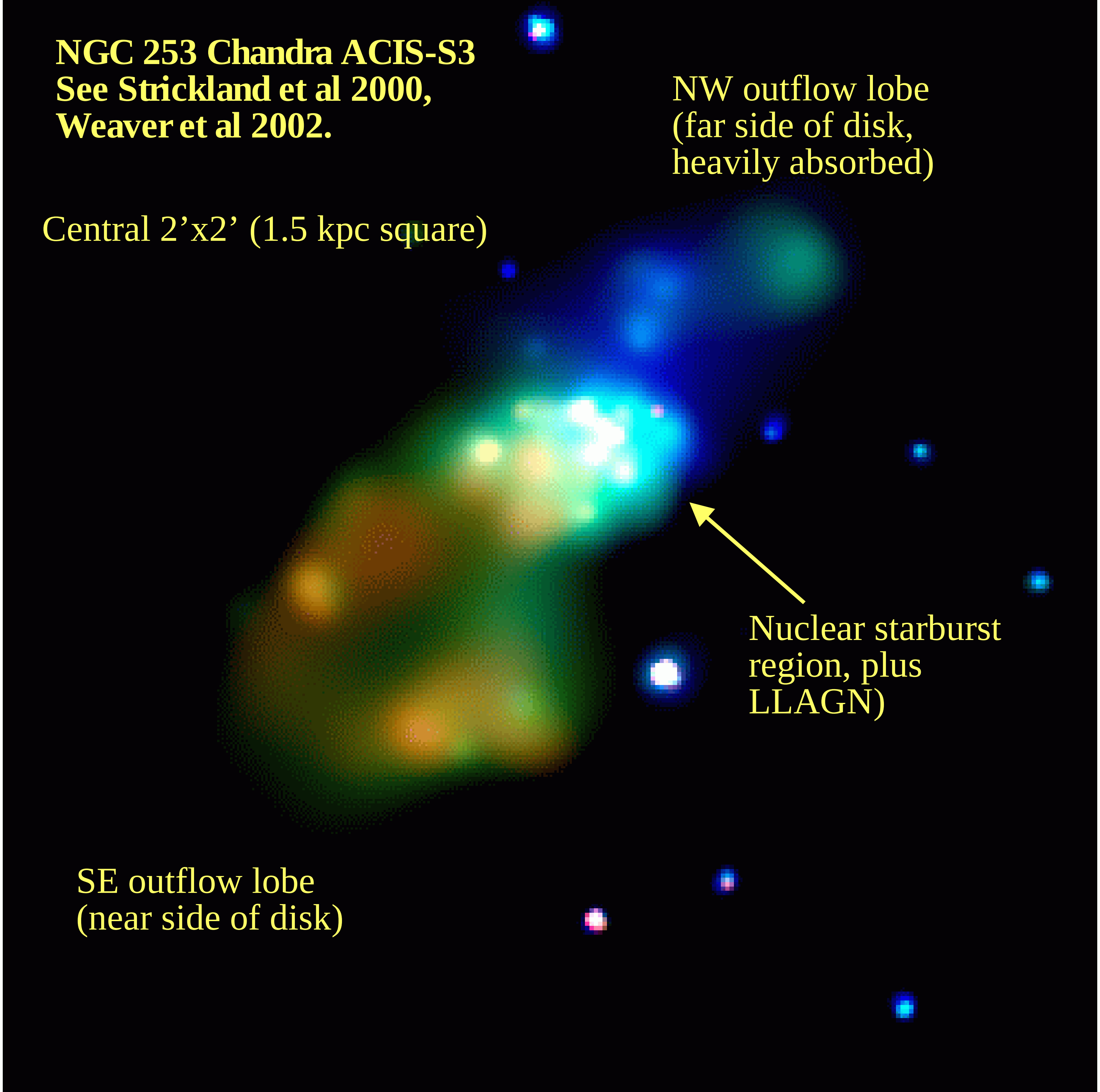
Thermal X-ray with enhanced **a**/Fe element ratio

SN-enriched metal loss in action?

Old and new views of NGC 3079

PSPC FWHM ~30" resolution ~ 2500 pc	HRI FWHM ~5" resolution ~ 415 pc	ACIS FWHM ~0.8" resolution ~ 66 pc





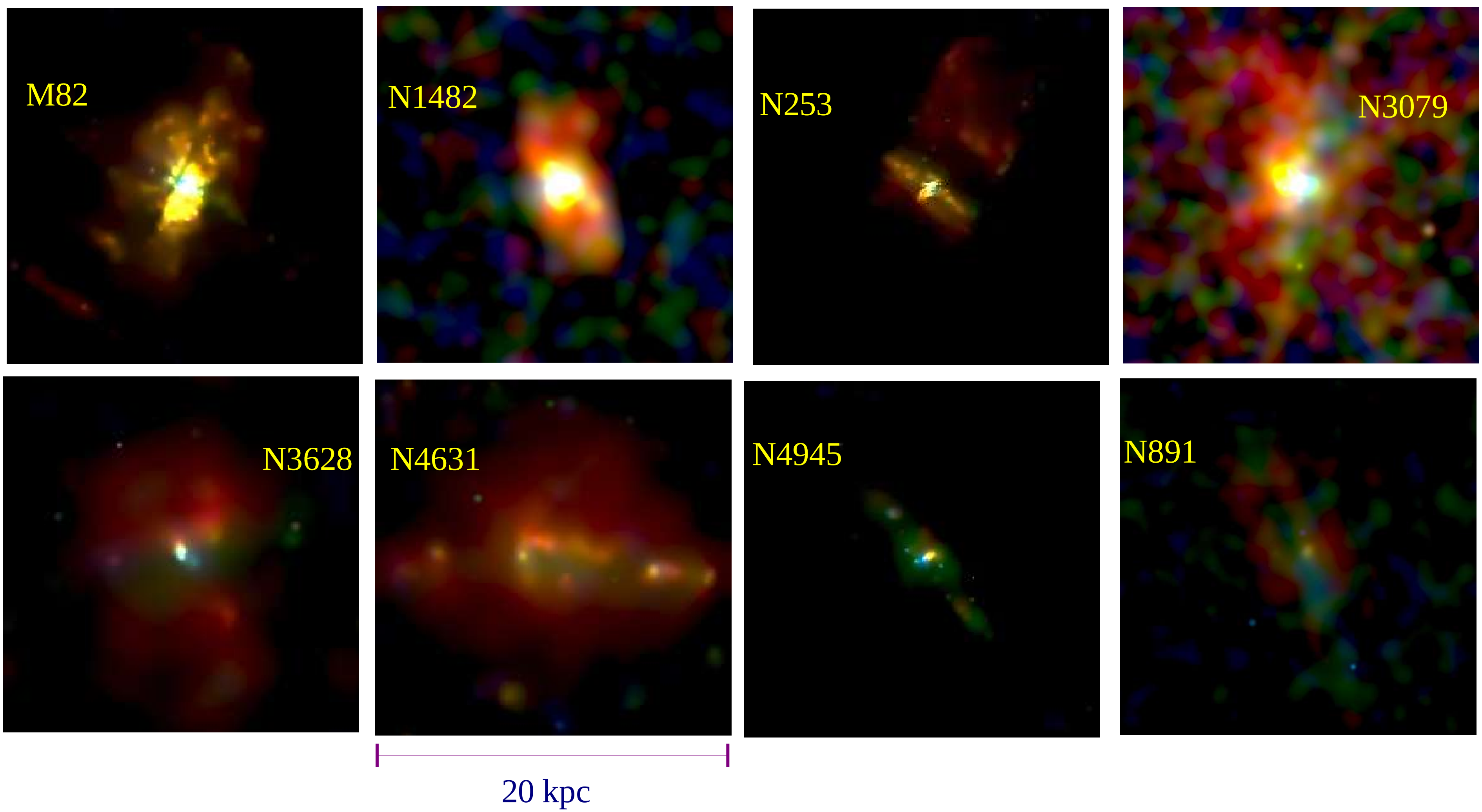
Energy coding

- 0.3-0.6 keV
- 0.6-1.1 keV
- 1.1-2.0 keV

For effects of complex spatial structure on spectral fitting, see Dahlem et al 2000, Weaver et al 2000.

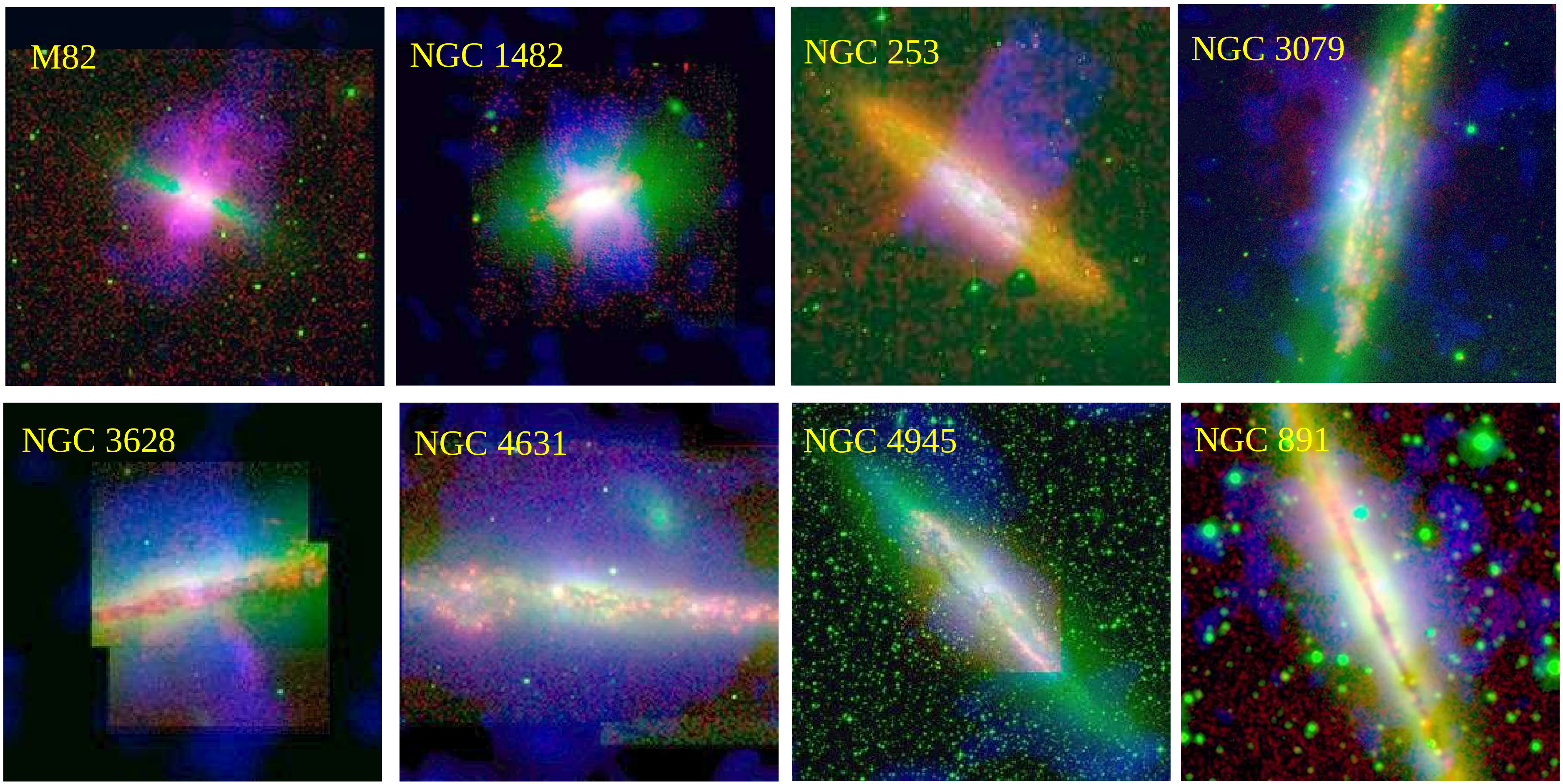
On larger scales --
emission from the halos of starburst galaxies

Diffuse emission only – all point sources removed.
Red = 0.3-1.0 keV, Green = 1.0-2.0 keV, Blue = 2.0-8.0 keV emission.
20 kpc x 20 kpc boxes, centered on the nucleus.
Identical sqrt intensity scale applied to all images.



Thermal X-ray emission from the halos of actively star-forming disk galaxies

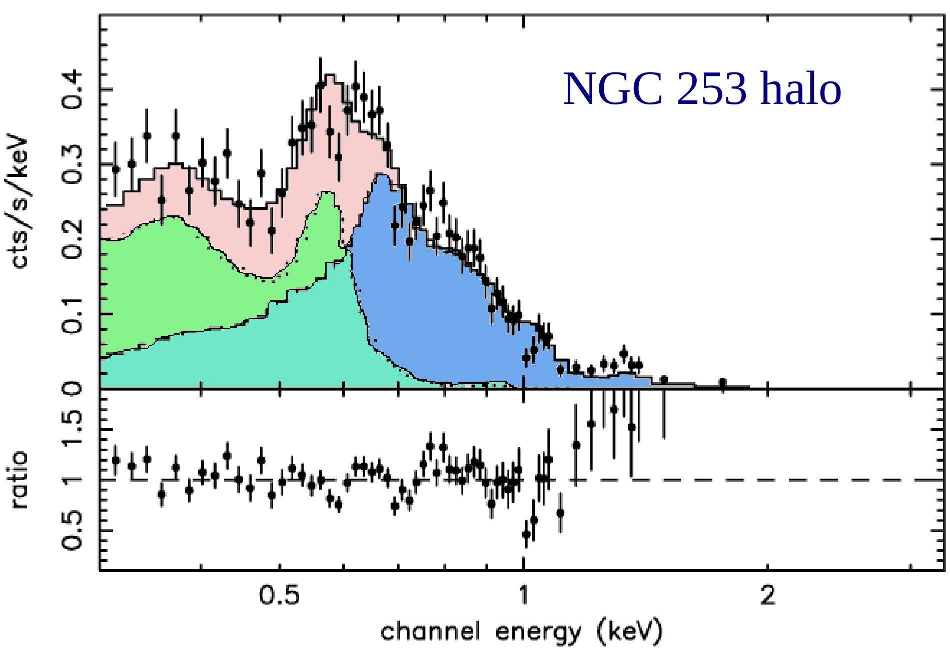
High-spatial resolution Chandra X-ray Observatory allows up to separate diffuse and point source emission. Red = Optical Hα emission (gas at T~10^4 K), Green = Optical R-band (stars), Blue = 0.3-2.0 keV emission (gas at T ~ 5×10^6 K). Each image is 20 kpc x 20 kpc (65 kLyr square) (from Strickland et al 2003)



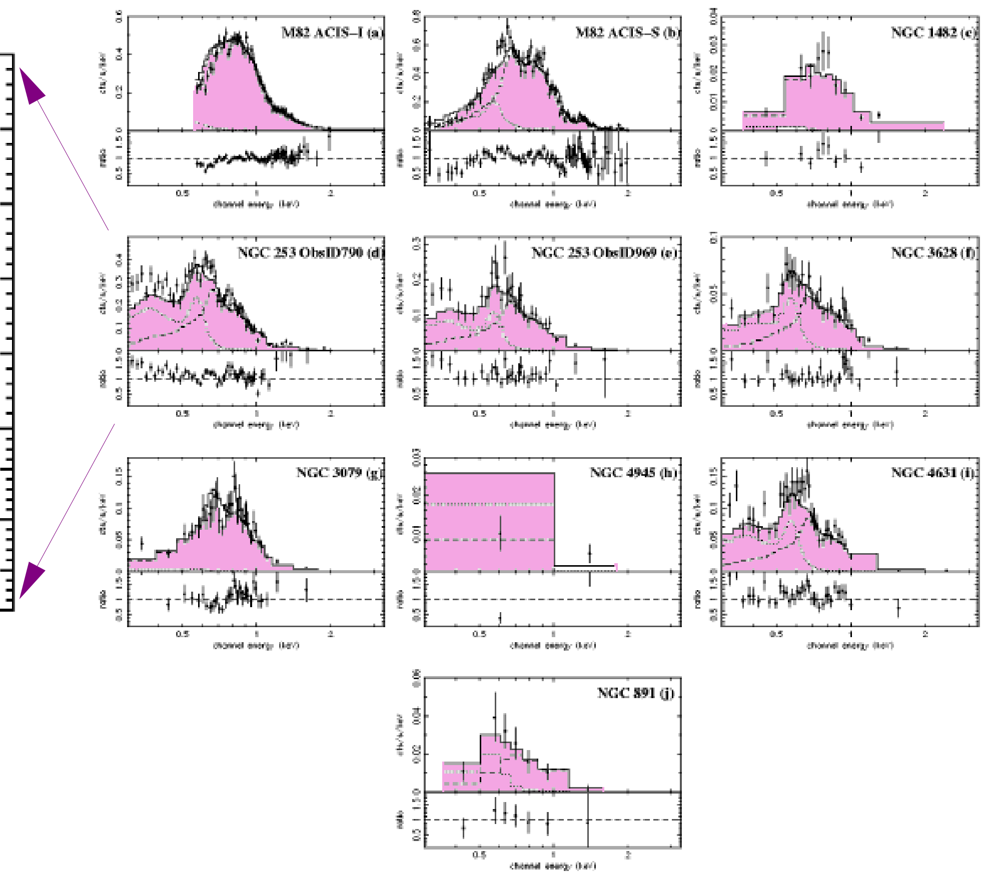
ACIS X-ray "spectroscopy" of halo emission

What is new about this analysis?

- Very robust removal of point sources.
- Separate diffuse emission in spectrally distinct disk and halo components (using hardness ratio analysis).
- Simultaneously fit ALL halo spectra with common 2-temperature CIE plasma model.



E (keV)

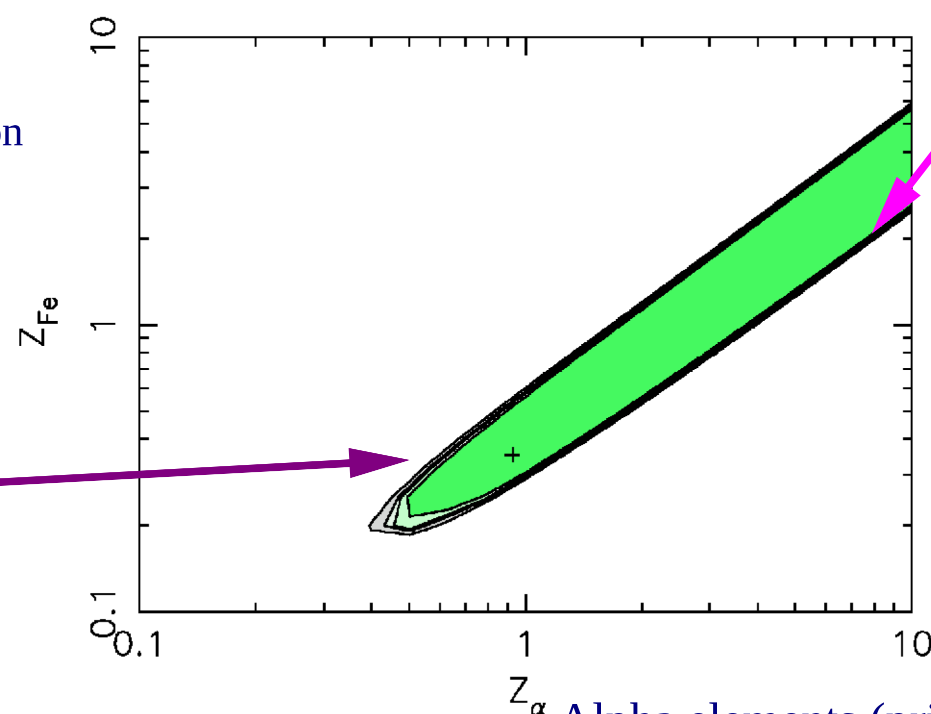


Metal abundances: Are we seeing metal loss in action?

- Gas phase **a**-to-Fe element ratio = 2.69 (+0.69,-1.02) (90% conf for 32 int.par) appears super-Solar, as was found with the Chandra observation of starbursting dwarf NGC 1569 (Martin, Kobulnicky & Heckman 2002).
- Absolute abundances (wrt to H) uncertain -- its degenerate.
- High a-to-Fe ratio does not automatically imply we are seeing SN-enriched gas. Shock-heated halo gas might well have Fe depleted onto dust...

Abundance of Iron
and refractories

Best fit value +
Contours are
68,90,95,99 %
confidence for
32 interesting params



Abundance for combined SN
and wind ejecta for 20 Myr-
old burst, from Silich et al
(2001, case 2WW)

Alpha elements (primarily O)

Enrichment vs. dusty gas

	[Fe/O]	[Si/O]	[Mg/O]	[Ne/O]
Observed values				
(Strickland et al 03)	-0.43	0.23	0.06	0.01
	+0.14,-0.08	<0.60	+0.21,-0.29	+0.14,-0.15
MW warm halo	-0.80	-0.30	-0.55	?
(Savage & Sembach '96)				
20 Solar mass SN				
slow convection	-0.49	0.34	-0.20	-0.45
fast convection	-0.46	0.00	0.09	0.22
(Umeda et al 2002)				

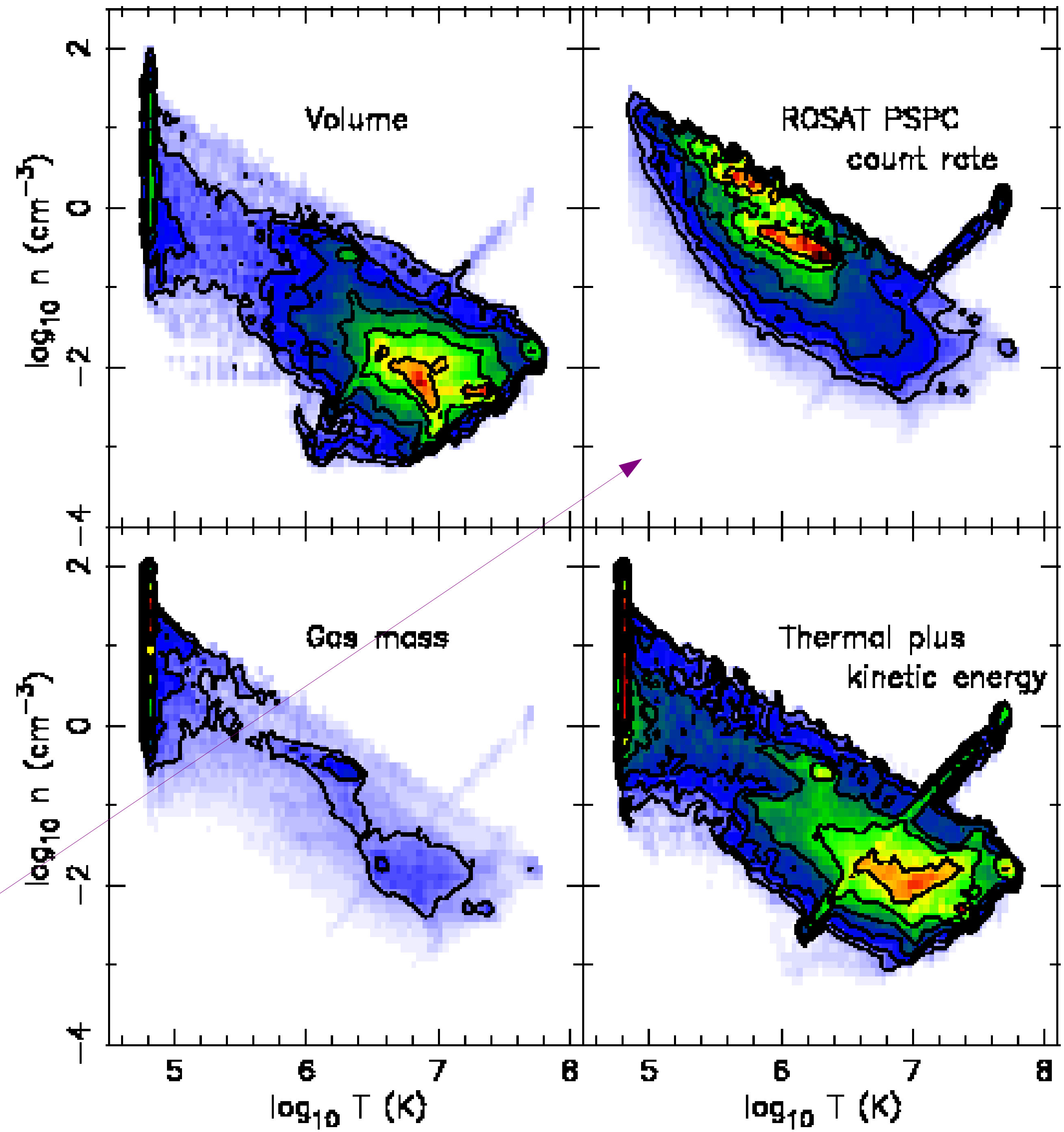
- Data consistent with either SN-enriched plasma or emission from dusty halo medium with moderate levels of depletion. Outstanding problems:
- Significant uncertainties remain in SN yields.
- Lack of absolute abundances (i.e wrt to H) --> require higher spectral resolution....

Another problem to worry about: irreducable spectral comlexity on small scales...

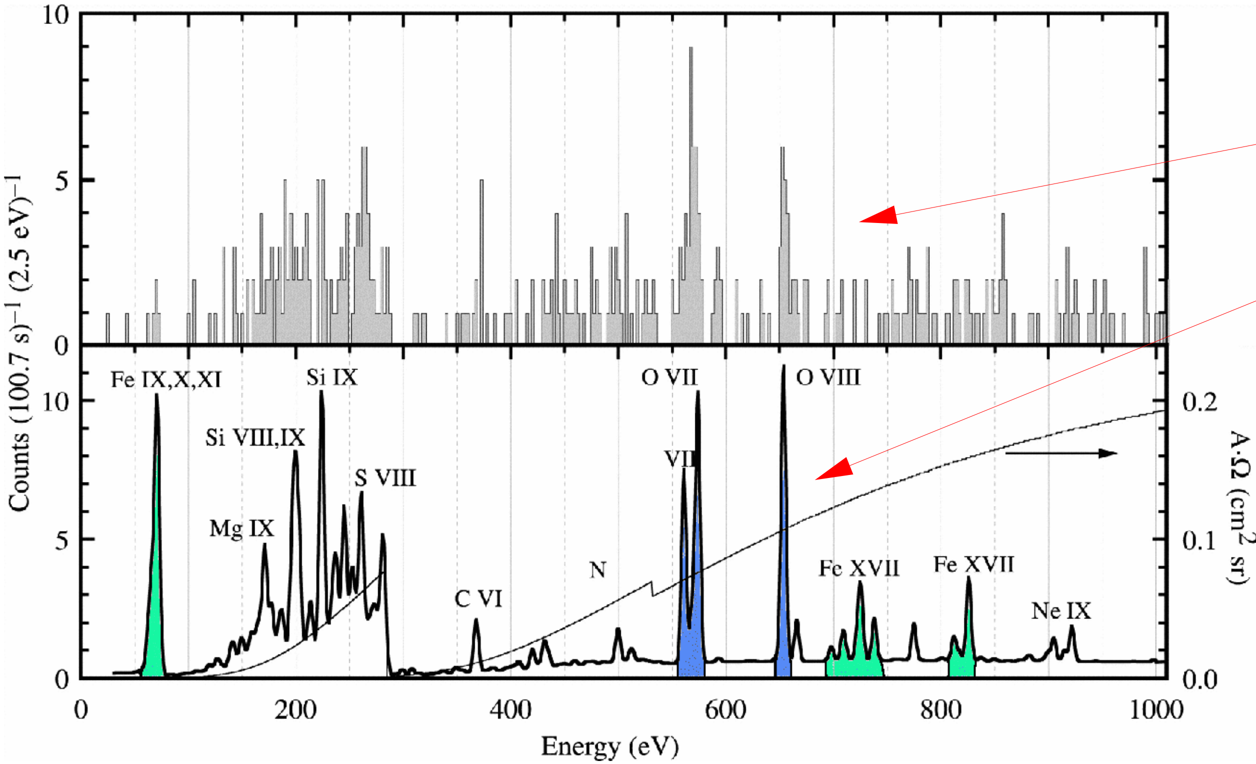
There is no reason to expect the emission comes from one or a few well-defined temperatures.

Ionization state may plausibly be CIE, or under or over ionized... Depends on exact origin of emission.

Theoretical prediction from high-resolution grid-based simulations (Strickland & Stevens 2000)



Element abundances of gas in our halo



Hot gas

Observed X-ray spectrum of our Galactic halo

Model Solar abundance spectrum

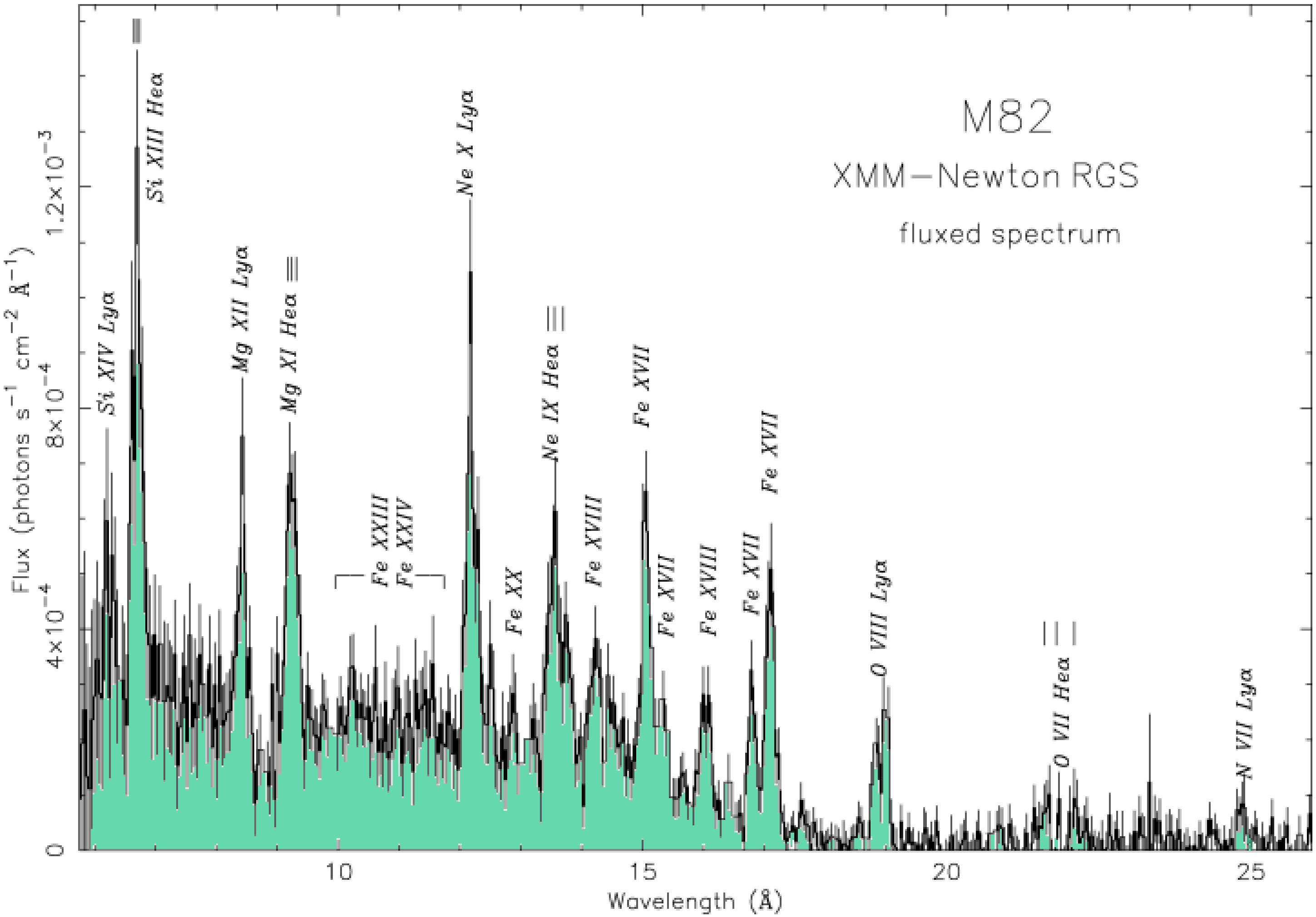
If O abundance ~ Solar, then Fe abundance < 0.14 x Solar -- depletion onto dust?

(McCammon et al 2002)

FUSE observations reveal that *some* of the "High velocity clouds" in the halo of the Milky Way have ~Solar O abundances, indicative that the gas was originally part of the disk.

Some clouds do have the low abundances expected of infall of intergalactic material, e.g. Complex C.

(Richter et al 2001)



A XMM (slit-less) grating spectrum of the *central* 2' (~2kpc) of M82

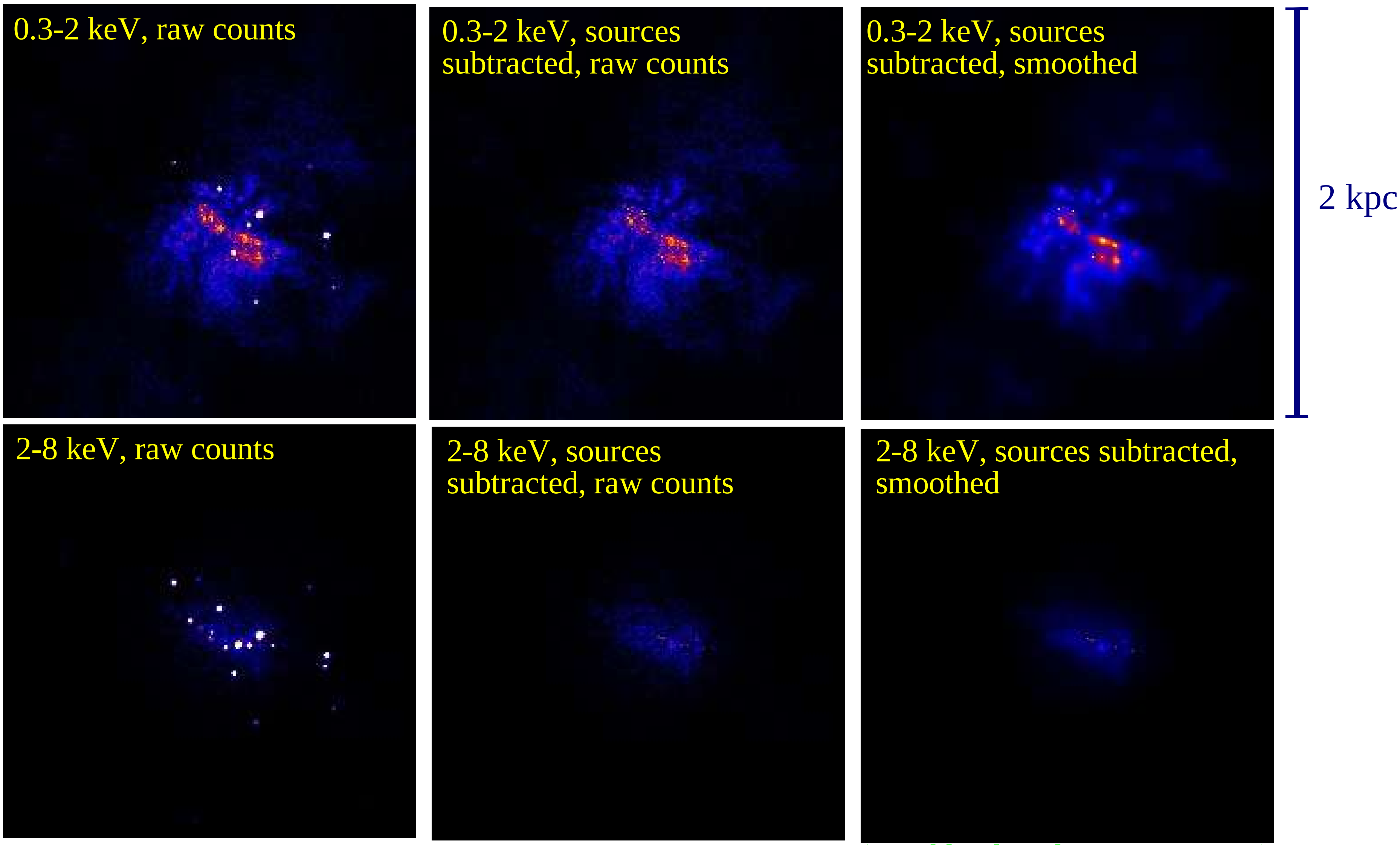
(Read & Stevens 2002)

Absolute abundances -> need to resolve the lines, and hence accurately measure intensities wrt to the continuum...

Need high spatial resolution and non-dispersive optics, to avoid contamination by X-ray binaries, LLAGN etc...

Point source contamination

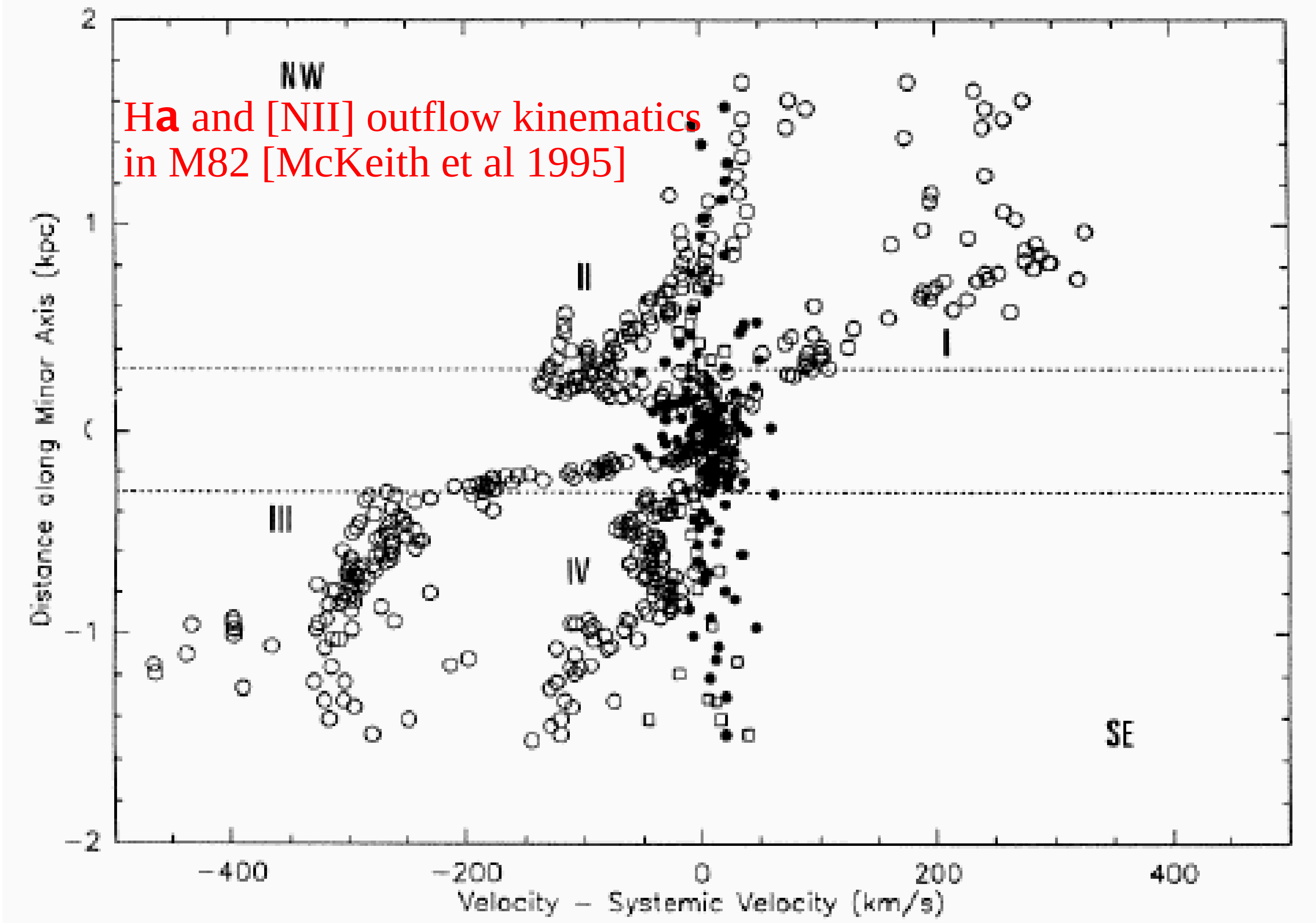
Require ~ arcsecond spatial resolution to exclude significant fraction of nuclear/disk region spectra being due to continuum sources.



(Strickland et al, in preparation)

Kinematic studies of winds...

No current observation measures of outflow velocity in gas hotter than ~3 x 10^5 K ...but hottest gas expected theoretically to have higher outflow velocity than other phases.

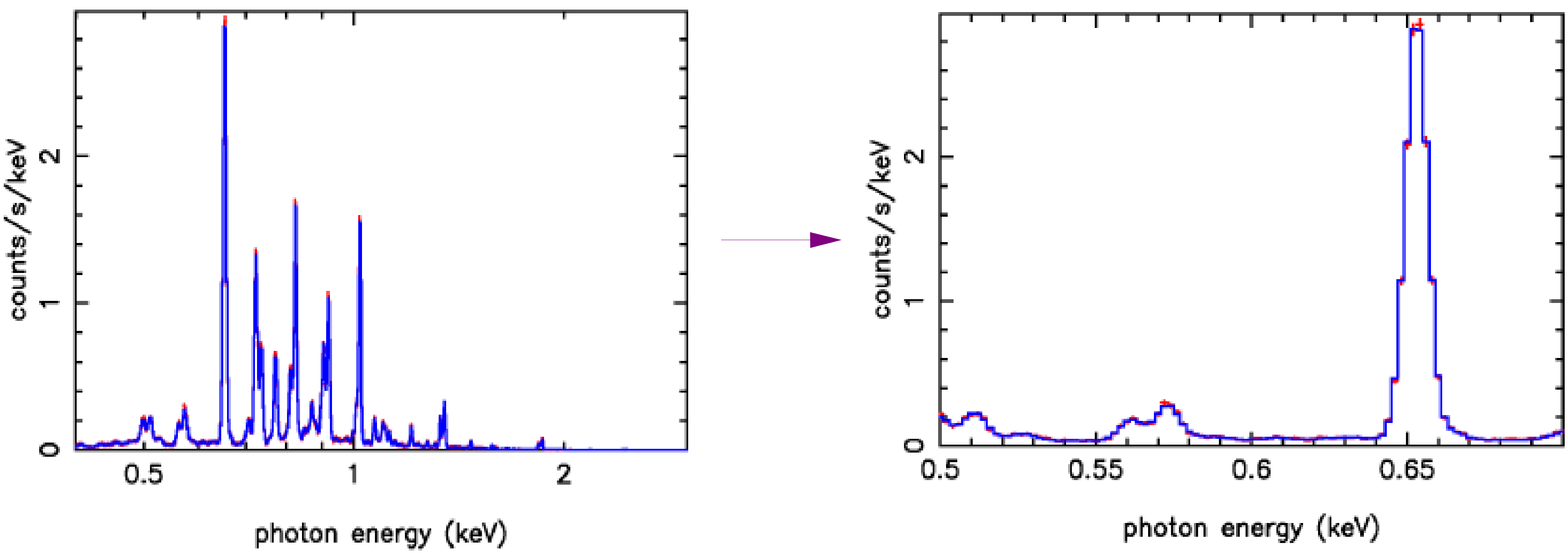


Hα and [NII] outflow kinematics in M82 [McKeith et al 1995]

A Con-X Appetizer: Spectroscopy with ASTRO-E2

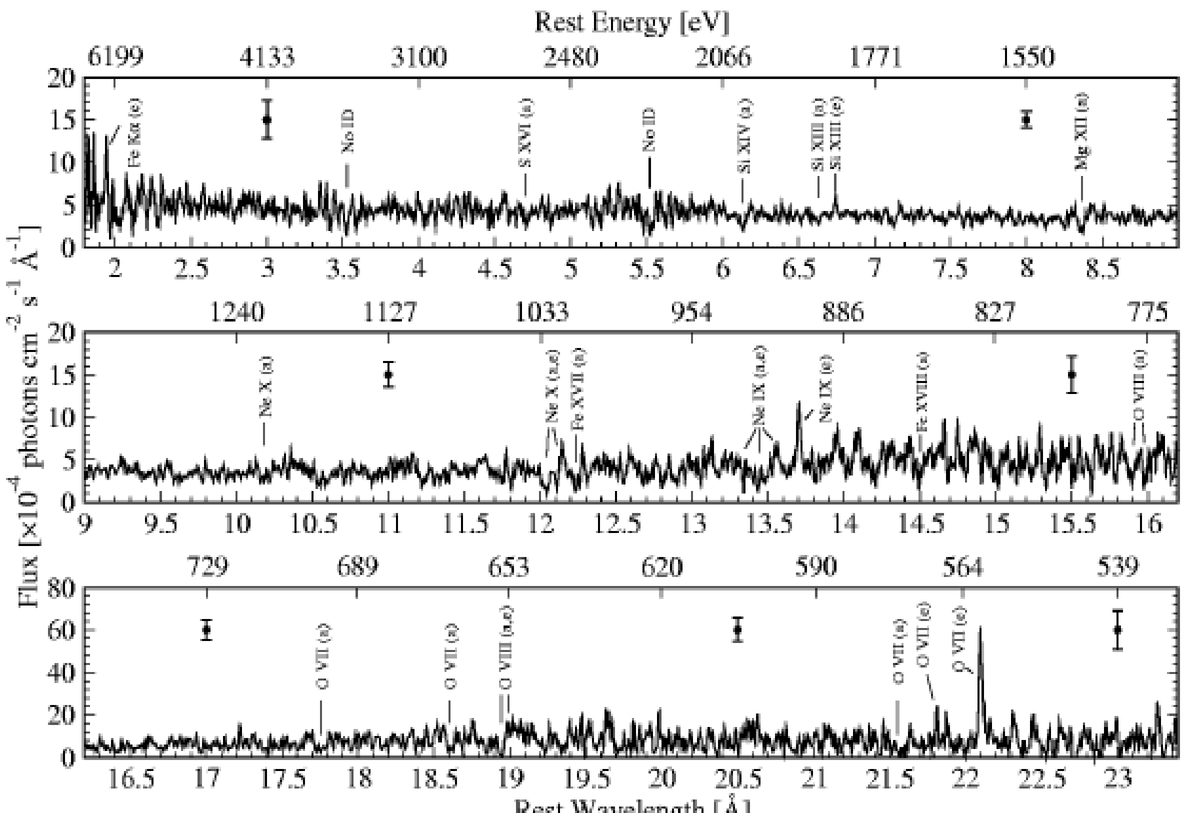
- Advantages to calorimeter:
  - Non-dispersive: Can do high resolution spectroscopy of diffuse emission!
  - Require spectral resolution of 0.2 eV at OVIII to get 100 km/s resolution for kinematic studies of edge-on winds. Beyond ASTRO-E's capabilities.

Simulated 1 Msec ASTRO-E2 observation of M82

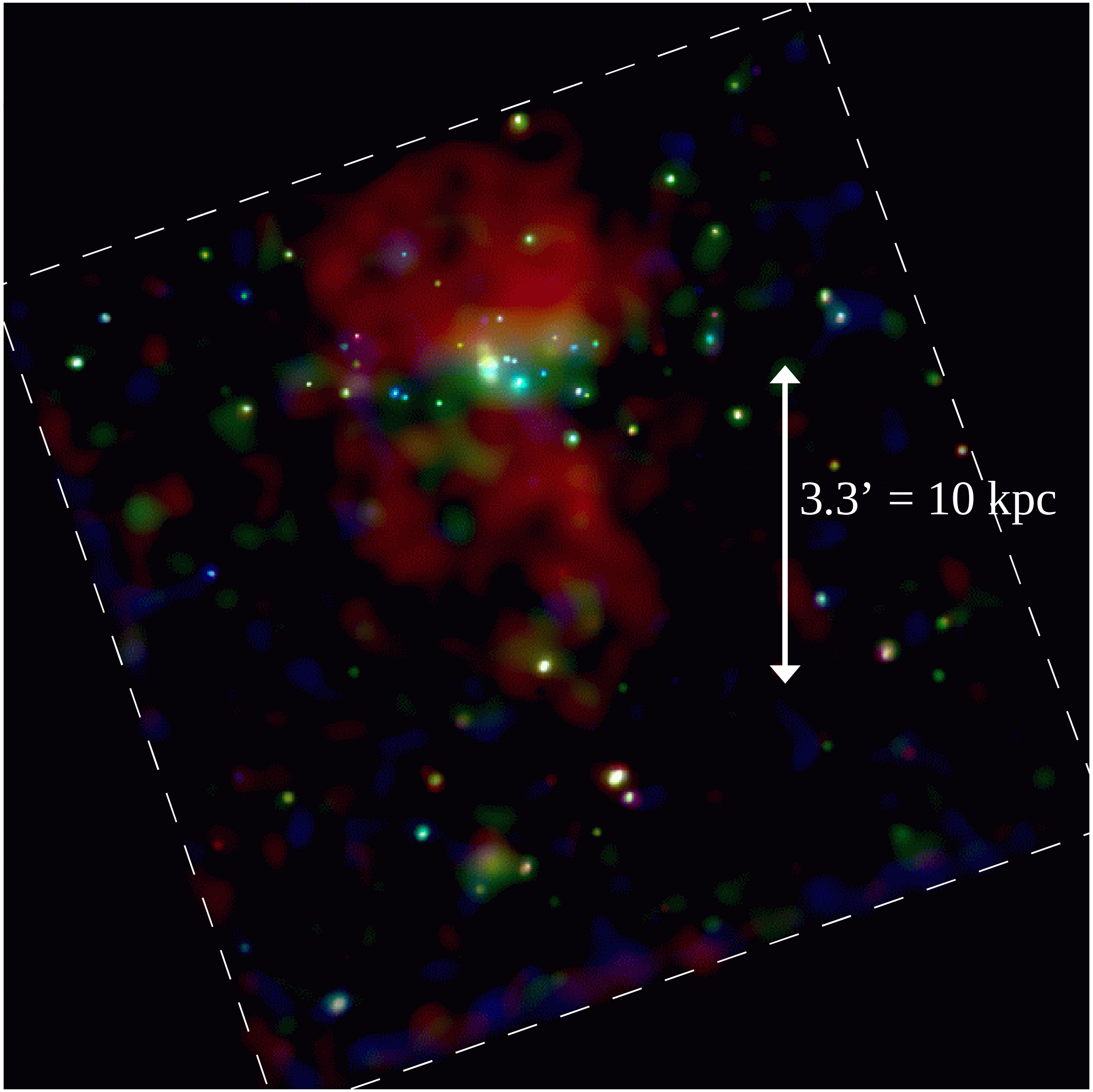


Absorption line X-ray spectroscopy

- Collinge et al (2001) Chandra HETG study of NGC 4051 warm absorber (Sy1) took ~ 80ks on $f_X \sim 2 \times 10^{-11}$ erg/s/cm^2 source – 32000 counts total.
- Warm absorbers provide nice approximation to superwinds – expected superwind hot gas column densities ~ 10^{21} cm^{-2}, velocities 200 -2000 km/s.
  - Don't want to use intrinsic nuclear AGN in starbursts as a light source.
  - Brightish AGN behind wind has $f_X \sim 7 \times 10^{-14}$ erg/s/cm^2.
  - IXOs provide alternative bright featureless (?) X-ray continuum (see next page).



Using IXOs as background sources



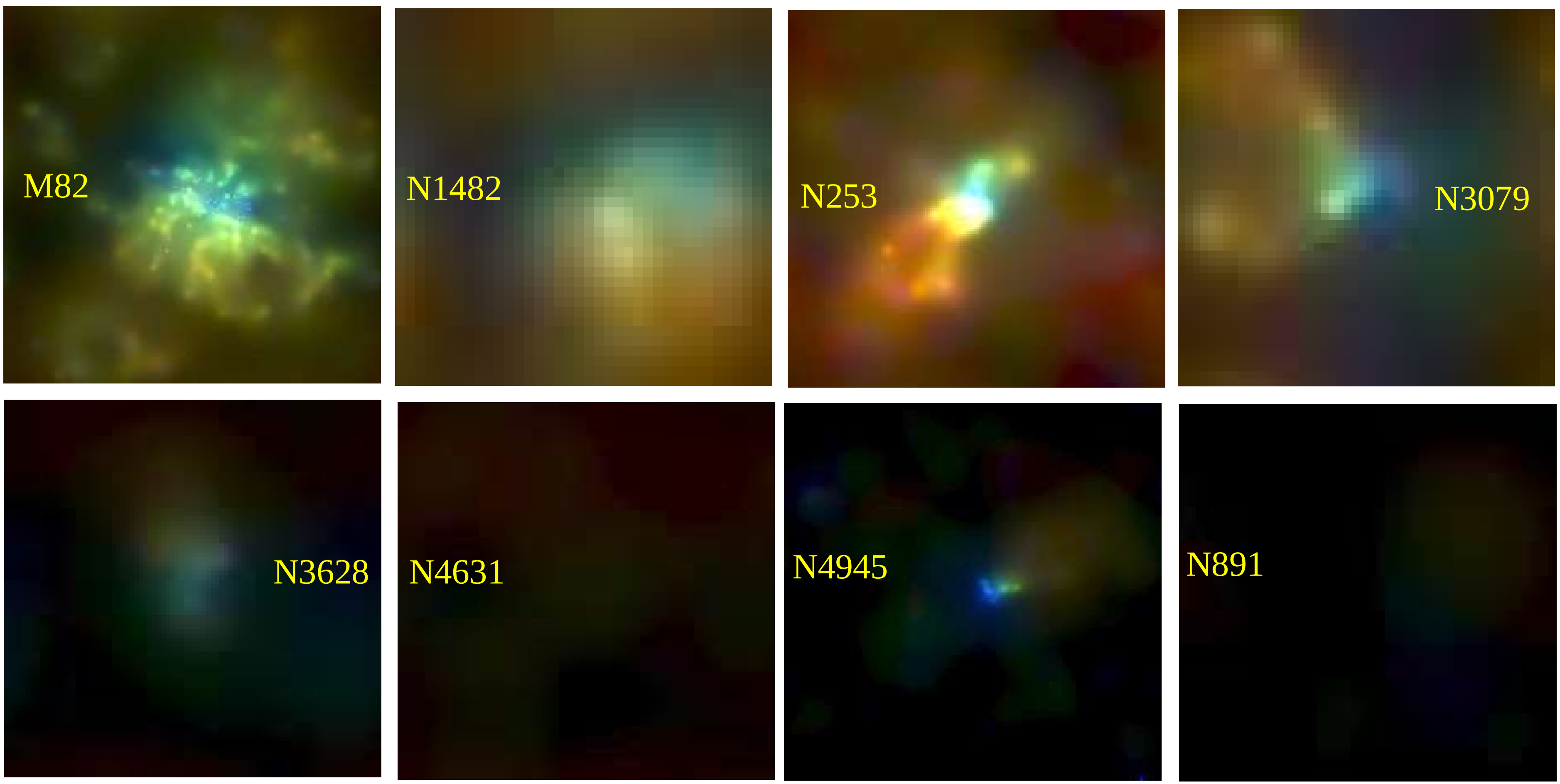
- Classic L_* starburst in the Leo triplet, D=10 Mpc.
- X-ray luminous, strongly variable X-ray source 900 pc from nucleus, ~ 35 % of entire X-ray emission from galaxy.
- NGC 3628 IXO:0.3-8.0 keV $f_X \sim 10^{-12}$ erg/s/cm^2 -> ASTRO-E count rate ~0.01 cts/s.
- M82 IXO, ~ ASTRO-E 0.05 cts/s.
- Require 600ks – 3 Msec exposures with ASTRO-E... Almost acceptable, but...

Summary: Lessons for the future...

- We've learnt a lot from Chandra & XMM how how to, and how not, to try to measure metal loss in action.....
  - Difficulty 1: Spatial variation of diffuse emission spectral properties, esp. in instruments with low spatial resolution.
  - Difficulty 2: Likewise, contamination by point sources must be avoided.
  - Difficulty 3: Complex physical problem, simple spectral models.
- Currently, we obtain super-Solar α/Fe ratios, possibly from enriched material but could well be dusty ambient disk/halo material. Should solve this issue soon with Chandra & XMM.
- To get absolute abundances, you need:
  - Good S/N on the continuum.
  - High spectral resolution (higher the better for kinematic studies)
  - Background must be low and not noisy.
- Con-X should look at the fainter halos, not the nuclei of starbursts.

Seen one wind, seen them all? No...

Diffuse emission only – all point sources removed.
Red = 0.3-1.0 keV emission, Green = 1.0-2.0 keV emission, Blue = 2.0-8.0 keV emission.
2 kpc x 2 kpc boxes, centered on the nucleus, identical sqrt intensity scale applied to all images.



Comparing optical emission with X-ray emission: Messier 82

Red: Hα+[NII], ~2 kpc x 2 kpc. (30” FUSE ap. M82-A) $f_{H\alpha}$ ~ 3.5e-13 erg/s/cm^2.

X-ray: red 0.3-1.0 keV, green 1-2 keV, blue 2-8 keV. (30” FUSE ap) f_X ~ 4.5e-13 erg/s/cm^2.